

# The continued spectral and temporal evolution of RX J0720.4–3125

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## ABSTRACT

RX J0720.4–3125 is the most peculiar object among a group of seven isolated X-ray pulsars (the so-called “Magnificent Seven”), since it shows long-term variations of its spectral and temporal properties on time scales of years. This behaviour was explained by different authors either by free precession (with a seven or fourteen years period) or possibly a glitch that occurred around  $\text{MJD} = 52866 \pm 73$  days.

We analysed our most recent *XMM-Newton* and *Chandra* observations in order to further monitor the behaviour of this neutron star. With the new data sets, the timing behaviour of RX J0720.4–3125 suggests a single (sudden) event (e.g. a glitch) rather than a cyclic pattern as expected by free precession. The spectral parameters changed significantly around the proposed glitch time, but more gradual variations occurred already before the (putative) event. Since  $\text{MJD} \approx 53000$  days the spectra indicate a very slow cooling by  $\sim 2$  eV over 7 years.

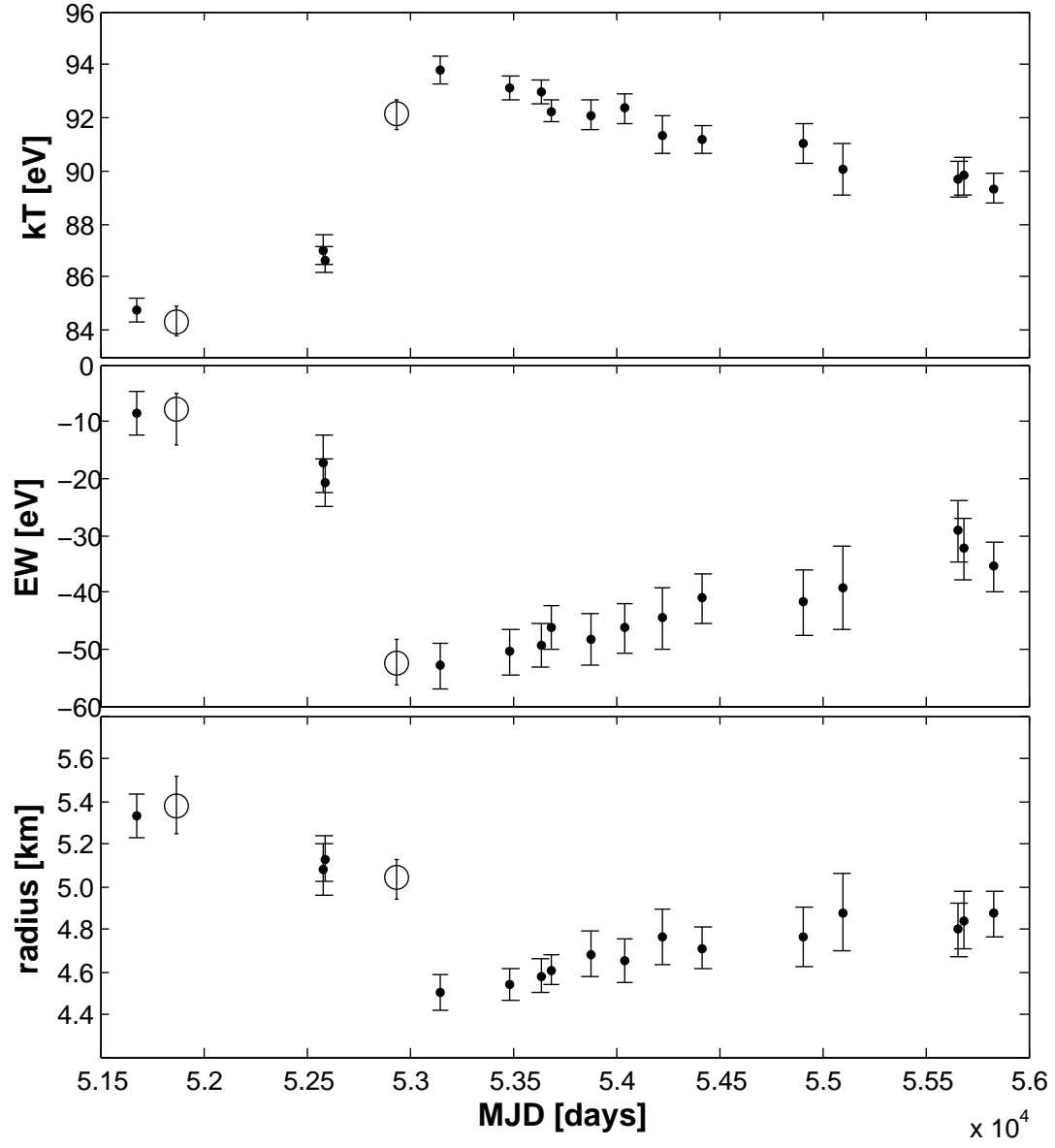
**Key words:** stars: neutron – pulsars: individual: RX J0720.4–3125

## 1 INTRODUCTION

The isolated neutron star (NS) RX J0720.4–3125 (RX J0720) belongs to a group of seven nearby ( $\lesssim 500$  pc) radio-quiet X-ray pulsars, the so-called “Magnificent Seven” (M7), discovered as bright X-ray sources in the ROSAT all-sky survey data. The M7 exhibit soft ( $T_{\text{eff}} \approx 40 - 100$  eV) blackbody-like X-ray spectra, in some cases with one or more broad absorption features that are interpreted as proton-cyclotron resonances or atomic transitions of bound species in a strong magnetic field,  $B \approx 10^{13} - 10^{14}$  G. Assuming magnetic dipole braking, similar magnetic field strengths can be derived from the standard spin-down formula for those sources for which pulse periods (all in the 3–12 s interval) and period derivatives are measured (see Kaplan & van Kerkwijk 2009a,b; van Kerkwijk & Kaplan 2008). The M7 have ages of 0.3–3 Myrs, as inferred by cooling curves or kinematics (Tetzlaff et al. 2010; Kaplan et al. 2002), while the characteristic ages are larger (2–5 Myrs). For a detailed review of the M7, we refer to Haberl (2007) and Kaplan & van Kerkwijk (2009a). RX J0720 is the second brightest member of the M7 and

it was identified as a pulsating X-ray source with a 8.39 s spin period in Haberl et al. (1997). Cropper et al. (2001) discovered a hardness ratio variation with pulse phase and a phase shift between the flux and the hardness ratio in the *XMM-Newton* data of RX J0720. Based on *XMM-Newton* RGS data, de Vries et al. (2004) showed that the energy-dependent change in the pulse profile is accompanied by a long term change of the X-ray spectrum<sup>1</sup>. The spectral changes were soon confirmed using *XMM-Newton* EPIC (Haberl et al. 2004) and *Chandra* LETG-S data (Vink et al. 2004). Furthermore, Haberl et al. (2006) found a phase lag between soft (0.12–0.40 keV) and hard (0.40–1.00 keV) photons, which changes over years. The *XMM-Newton* spectra of RX J0720 are best modelled with a blackbody plus a broad absorption feature at  $\sim 0.3$  keV (Haberl et al. 2004). Haberl et al. (2006) reported variations of the blackbody temperature, the equivalent width of the

<sup>1</sup> Note that initially the changes at long wavelengths were overestimated, as the *XMM-Newton* RGS instrument suffers from a decline in sensitivity in the long wavelength band.



**Figure 1.** Spectral properties of RX J0720, as listed in Table 2.

**Table 1.** The three new *XMM-Newton* observations (all with thin filter) performed after Hohle et al. (2010). We list the net counts in soft band (0.12–0.40 keV) and hard band (0.40–1.00 keV). The soft photons from the EPIC-MOS data are not used in this work.

MJD [days]/ obsID	EPIC setup	eff exp [ks]	net cts soft	net cts hard
55662 / 0650920101	pn /FF	14.41	53014	38114
	MOS1 /SW	20.47	–	10429
	MOS2 /SW	19.86	–	10260
55684 / 0670700201	pn /FF	13.10	48680	35436
	MOS1 /SW	22.02	–	11934
	MOS2 /SW	23.20	–	12224
55835 / 0670700301	pn /FF	22.18	86713	58888
	MOS1 /SW	25.82	–	12975
	MOS2 /SW	25.83	–	13042

absorption feature and the blackbody normalisation of RX J0720 compatible with a periodic behaviour with a long term period of  $P_{\text{long}} \approx 7.1$  yrs. However, the data used in Haberl et al. (2006) spanned only 4.5 yrs, i.e. not the complete cycle of the tentative period.

The period derivative of RX J0720 was first estimated by Zane et al. (2002) and subsequently further constrained by Cropper et al. (2004) and Kaplan & van Kerkwijk (2005) as new observations become available. Haberl et al. (2006) found that periodical phase residuals were possibly present (again with  $P_{\text{long}} \approx 7.5$  yrs) in the timing solution of RX J0720 with a constant value of  $\dot{P} = 0.698(2) \times 10^{-13} \text{ s s}^{-1}$  (Kaplan & van Kerkwijk 2005). The spectral and temporal variations of RX J0720 are unique among the M7 and were explained either by free precession (Haberl et al. 2006; Haberl 2007; Hohle et al. 2009), or a glitch that occurred at MJD =  $52866 \pm 73$  days (van Kerkwijk et al. 2007). Both scenarios, free precession and the glitch event, have their drawbacks, as discussed in van Kerkwijk et al. (2007) and Hohle et al. (2009, 2010). The most recent overview of the spectral evolution of RX J0720 was given in Hohle et al. (2009). Since then, our team performed five further *XMM-Newton* observations. Moreover, three *Chandra* observations were obtained after the last update of the timing solution (Hohle et al. 2010). Here, we present our analysis and results for these more recent data sets in connection with further spectral and temporal evolution of RX J0720.

## 2 DATA AND DATA REDUCTION

In addition to Hohle et al. (2009) we analyse here five new *XMM-Newton* observations, two of which (revolutions 1700 and 1792) were already used for the timing in Hohle et al. (2010), but not to investigate the spectral behaviour. We reduced all available *XMM-Newton* data of RX J0720 with the standard *XMM-Newton* Science Analysis System (SAS) version 11.0 using the EPCHAIN and EMCHAIN tasks for EPIC-pn (Strüder et al. 2001) and both EPIC-MOS (Turner et al. 2001), respectively. For details on the analysis of the *XMM-Newton* data (i.e. data extraction and good time interval, GTI, filtering) we refer to Hohle et al. (2009, 2010, 2012).

We list the three new data sets (neither used for timing, nor for spectroscopy so far) in Table 1. EPIC-MOS was always used in small window (SW) mode with a time resolution of 0.3 s, whereas EPIC-pn was used in full frame mode (FF, time resolution of 73.4 ms).

We analysed the *Chandra* HRC-S/LETG (Juda 1996) data with CIAO 4.1 and refer to Hohle et al. (2010, 2012) for details, both on the data reduction and the most recent *Chandra* HRC-S/LETG observations (SRON and MPE guaranteed time data) of RX J0720.

Due to the lack of a sufficient amount of photons for the individual spectra, we use the *Chandra* data for timing analysis only.

## 3 RESULTS

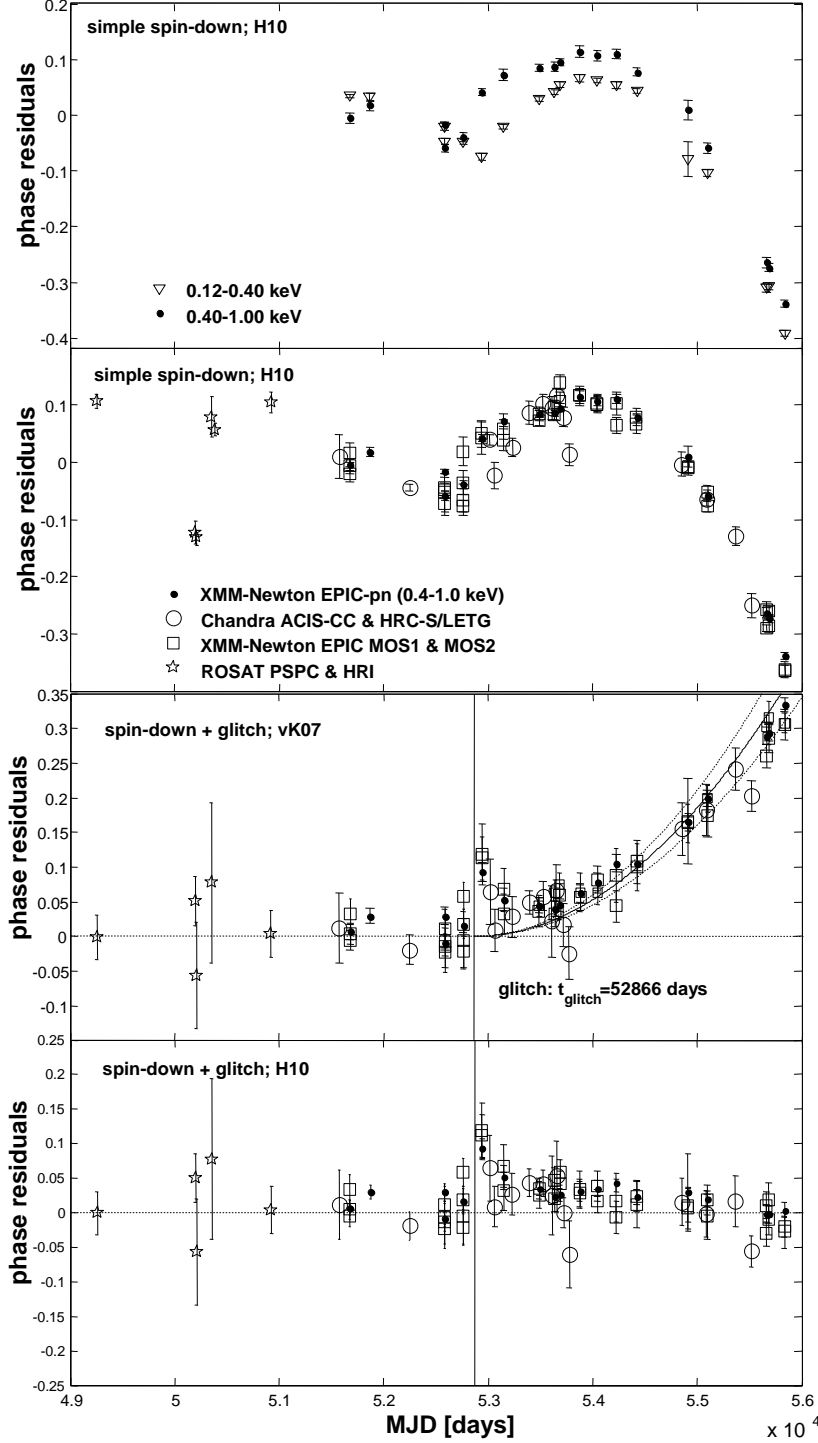
### 3.1 Spectral behaviour

To investigate the spectral evolution of RX J0720 we first fitted all sixteen EPIC-pn spectra obtained in full frame mode with thin filter in one session using XSPEC12. We used the model *phabs\*(bbodyrad+gaussian)*, as also used in Haberl et al. (2004, 2006); Haberl (2007); Hohle et al. (2009) and Hohle et al. (2012), where *gaussian* is used to account for the broad absorption feature at 0.3 keV. The simultaneous fit of the sixteen EPIC-pn datasets results in  $\chi^2/\text{d.o.f} = 1.23$  with 2374 degrees of freedom. We obtain  $N_{\text{H}} = 0.984 \pm 0.050 \times 10^{20} \text{ cm}^{-2}$  for interstellar absorption,  $E_{\text{line}} = 311.9 \pm 5.0 \text{ eV}$  for the central energy and  $\sigma = 64.4 \pm 3.5 \text{ eV}$  for the line width of the broad absorption feature (all errors denote 90% confidence level). These three parameters were assumed to be constant for all observations, as in previous works (Haberl et al. 2004, 2006; Haberl 2007; Hohle et al. 2009). The blackbody temperature (kT), emitting radius (R, computed assuming a distance of  $D = 300 \text{ pc}$ , see Kaplan et al. 2007 and Eisenbeiss 2011), and the line equivalent width (EW) were allowed to vary between the observations.

Due to cross-calibration and pile-up issues for the normalisation (see Haberl et al. 2004 for a detailed discussion), the data obtained with other instrument setups (revolutions 0175 with medium filter and revolution 0711 in small window mode and medium filter) were fitted separately, but fixing  $N_{\text{H}}$ ,  $E_{\text{line}}$  and  $\sigma$  at the values obtained from the simultaneous fit of the sixteen EPIC-pn spectra performed in full frame mode with thin filter, see Table 2 and Figure 1. As reported already in Haberl et al. (2006), the temperature, size of the emitting area and equivalent width underwent major changes around MJD = 53000 days, but since then (i.e. over the last seven years), all three parameters changed only gradually. *XMM-Newton* observations cover now a time span of almost 12 yrs, hence a 7.5 yrs period can be excluded. A 14 yrs period seems unlikely, since if one extrapolates the spectral evolution (Figure 1) for two further years, the spectral properties are still significantly different to their initial values.

### 3.2 Timing

Applying the “all data” solution with constant spin-down, Hohle et al. (2010) found that the phase residuals of



**Figure 2.** Phase residuals of RX J0720 after applying the phase coherent “all data” timing solution in Hohle et al. (2010, H10) with constant spin-down (upper two panels). The top panel illustrates the variable phase shift between soft (0.12-0.40 keV) and hard (0.40-1.00 keV) photons seen in the EPIC-pn data. The glitch solution proposed by van Kerkwijk et al. (2007, vK07) fits well the data available at this time (MJD = 53500 days), but poorly represents the data at later epochs (third panel). The later (deviant) points require an additional quadratic term (shown with its  $1\sigma$  uncertainty) to be explained; this corresponds to a modification of the spin-down parameter  $\dot{f}$  for  $t > t_g$  (Hohle et al. 2010). The phase residuals from the most recent observations (after MJD = 55100 days) are consistent with the modified glitch solution (lower panel). The glitch time  $t_g$  at MJD =  $52866 \pm 73$  days is indicated by the solid vertical line in the lower two panels. All error bars correspond to  $1\sigma$  confidence.

**Table 2.** Effective temperature (kT) and radiation radius (both measured at infinity), flux and equivalent width (EW) of the broad absorption feature derived from *XMM-Newton* EPIC-pn spectra (see also Figure 1). All observations were performed in full frame mode with thin filter, except rev. 0175 (medium filter) and rev. 0711 (small window mode with medium filter), that are highlighted in italic. All errors denote 90% confidence level.

ReNo	MJD [days]	kT [eV]	radius [km]	EW [eV]	flux 0.12-1.0 keV [ $10^{-11}$ ergs cm $^{-2}$ s $^{-1}$ ]
0078	51677	84.74 ± 0.43	5.33 $^{+0.10}_{-0.10}$	−8.9 $^{+3.8}_{-3.9}$	1.0903 $^{+0.0094}_{-0.0100}$
<i>0175</i>	<i>51870</i>	84.32 ± 0.57	5.38 $^{+0.13}_{-0.14}$	−7.9 $^{+2.9}_{-6.1}$	1.1061 $^{+0.0062}_{-0.0062}$
0533	52585	87.01 ± 0.57	5.08 $^{+0.12}_{-0.12}$	−17.2 $^{+5.0}_{-5.1}$	1.0914 $^{+0.0092}_{-0.0108}$
0534	52587	86.63 ± 0.48	5.13 $^{+0.10}_{-0.10}$	−20.7 $^{+4.0}_{-4.3}$	1.0800 $^{+0.0060}_{-0.0080}$
<i>0711</i>	<i>52940</i>	92.12 ± 0.56	5.04 $^{+0.10}_{-0.11}$	−52.3 $^{+4.0}_{-3.8}$	1.2638 $^{+0.0064}_{-0.0096}$
0815	53148	93.80 ± 0.51	4.50 $^{+0.08}_{-0.09}$	−52.8 $^{+4.0}_{-4.1}$	1.1007 $^{+0.0066}_{-0.0074}$
0986	53489	93.14 ± 0.45	4.54 $^{+0.08}_{-0.08}$	−50.5 $^{+4.0}_{-4.0}$	1.0883 $^{+0.0075}_{-0.0066}$
1060	53636	92.97 ± 0.47	4.58 $^{+0.08}_{-0.08}$	−49.2 $^{+3.8}_{-3.9}$	1.1028 $^{+0.0064}_{-0.0055}$
1086	53687	92.24 ± 0.41	4.61 $^{+0.07}_{-0.07}$	−46.2 $^{+3.8}_{-3.9}$	1.0860 $^{+0.0061}_{-0.0080}$
1181	53877	92.11 ± 0.59	4.68 $^{+0.10}_{-0.11}$	−48.2 $^{+4.5}_{-4.6}$	1.1061 $^{+0.0039}_{-0.0083}$
1265	54045	92.35 ± 0.58	4.65 $^{+0.10}_{-0.10}$	−46.1 $^{+4.2}_{-4.7}$	1.1130 $^{+0.0080}_{-0.0100}$
1356	54226	91.35 ± 0.71	4.76 $^{+0.13}_{-0.13}$	−44.4 $^{+5.3}_{-5.7}$	1.1110 $^{+0.0040}_{-0.0120}$
1454	54421	91.17 ± 0.54	4.71 $^{+0.10}_{-0.10}$	−40.9 $^{+4.1}_{-4.6}$	1.0900 $^{+0.0060}_{-0.0079}$
observations since Hohle et al. (2009)					
1700	54912	91.05 ± 0.75	4.76 $^{+0.14}_{-0.14}$	−41.6 $^{+5.6}_{-5.9}$	1.1042 $^{+0.0096}_{-0.0120}$
1792	55096	90.08 ± 0.96	4.87 $^{+0.18}_{-0.18}$	−39.1 $^{+7.1}_{-7.2}$	1.1067 $^{+0.0110}_{-0.0149}$
2076	55662	89.69 ± 0.65	4.80 $^{+0.12}_{-0.13}$	−29.1 $^{+5.2}_{-5.5}$	1.0841 $^{+0.0098}_{-0.0120}$
2087	55684	89.80 ± 0.71	4.84 $^{+0.13}_{-0.14}$	−32.4 $^{+5.2}_{-5.5}$	1.0990 $^{+0.0040}_{-0.0081}$
2163	55835	89.34 ± 0.54	4.87 $^{+0.10}_{-0.11}$	−35.3 $^{+4.1}_{-4.5}$	1.0776 $^{+0.0063}_{-0.0110}$

RX J0720 have shown a long term behaviour with a possible periodic pattern yielding a 7-9 yr or a 14-16 yr period (depending on assumptions) until summer 2010 (MJD  $\approx$  55400 days). Therefore, it was expected that the phase residuals (which were negative at the time of the previous investigation) will approach zero for the next observations. However, the phase residuals still reach large and negative values, if the “all data” solution in Hohle et al. (2010) is applied (Figure 2, upper two panels) to the new data. Also the variable phase shift between soft and hard photons (Figure 2, upper panel) stays constant since the last observations, whereas it was expected that the phase shift will reverse sign again, like it occurred around MJD = 53000 days, if RX J0720 precesses.

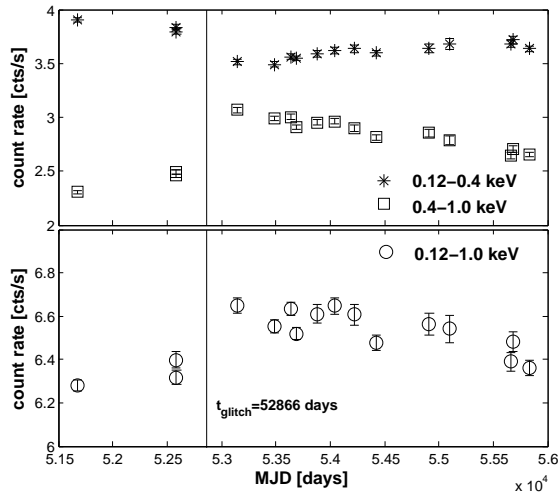
van Kerkwijk et al. (2007) proposed a “glitch solution” to explain the timing behaviour of RX J0720, that well fits the data available at that time (see Figure 2, third panel), but does not represent the data after MJD = 53500 days. Hohle et al. (2010) modified the “glitch solution” of van Kerkwijk et al. (2007) by including a change in spin-down  $\dot{f}_c$ , valid for  $t > t_g$  (Table 3). This term corrects the drift of the phase residuals in Figure 2 (third panel), since the time span available for van Kerkwijk et al. (2007) was too short for a more accurate extrapolation of the phase. Including  $\dot{f}_c$ , even the phase residuals of the data that were not available to Hohle et al. (2010, i.e., after MJD = 55100 days) are consistent with zero (Figure 2, lowest panel). Hence, the “glitch solution” of van Kerkwijk et al. (2007) with the update of Hohle et al. (2010) models the timing behaviour of RX J0720 much better than a timing solution with constant spin-down.

**Table 3.** The timing parameters of the glitch solution (van Kerkwijk et al. 2007) for RX J0720 with  $\dot{f}_c$  for  $t > t_g$ . The numbers in parenthesis indicate the  $2\sigma$  errors. The phase is determined by  $\Phi(t) = \Phi(t_o) + f(t - t_o) + 0.5 \cdot \dot{f}(t - t_o)^2 - 0.5 \cdot \dot{f}_c(t - t_o)^2 + \Delta\Phi_g(t)$ , with  $\Delta\Phi_g(t) = -\Delta f(t - t_o) - 0.5 \cdot \Delta \dot{f}(t - t_o)^2$  and  $\Delta\Phi_g(t) = 0$  for  $t > t_g$ .

$t_o$ [MJD]	53,010.2635667(10)
$f$ [Hz]	0.1191736716(9)
$\dot{f}$ [ $10^{-15}$ Hz/s]	−1.04(3)
$t_g$ [MJD]	52,866(73)
$\Delta f$ [nHz]	4.1(12)
$\Delta \dot{f}$ [ $10^{-17}$ Hz/s]	−4(3)
$\dot{f}_c$ [ $10^{-17}$ Hz/s]	−1.11(20)

## 4 DISCUSSION

The present data of RX J0720 do not support a cyclic behaviour with a period in the 7 to 14 year range in the spectral and timing properties of the source. However, the measured blackbody temperature is still declining and, by extrapolating the linear trend (since the proposed glitch time  $t_g = 52866 \pm 73$  days), RX J0720 will reach its initial state in autumn 2019. It is of interest to follow this decline and assessing whether the temperature will finally stabilise at the pre-2003 value. This requires a monitoring for at least 20 years in total (out of which eleven years have been already covered) to reveal any long term periodicity. It is not possible to explain both, the spectral and temporal changes of RX J0720 by precession with a self-consistent model similar to that discussed in Haberl et al. (2006), figure 5 therein. This might reflect the lack of knowledge regarding to the exact emission geometry (spot shape, temperature distribution, atmospheric effects etc.) of this NS.



**Figure 3.** The evolution of the count rates of RX J0720 in the soft and hard band (upper panel) and the total count rate (lower panel). The data are obtained for the observations performed with *XMM-Newton* EPIC-pn in full frame mode with thin filter (errors denote 90% confidence level).

The ‘glitch solution’ of van Kerkwijk et al. (2007) fits well the phase residuals, if the modification by Hohle et al. (2010) is applied. The jump in frequency at  $\text{MJD} = 52866 \pm 73$  days would correspond to the gain of angular momentum imparted by a mass of  $10^{20} - 10^{21}$  g accreted by the NS (van Kerkwijk et al. 2007). Hence, the glitch might have been caused by an accretion event e.g. the impact of an asteroid. Recently, some evidence for a disc or a dense ( $n_H = 10 - 10^{10} \text{ cm}^{-3}$ ) ambient medium around RX J0720 was discussed (Hambaryan et al. 2009; Hohle et al. 2012). This (still) hypothetic disc may host material for such an impact (see discussion in Hohle et al. 2012). However, as illustrated in Figure 1, the spectral changes occurred already before  $\text{MJD} = 52866 \pm 73$  days and this would point rather to a slow change than a sudden event. Also, the variable phase lag between soft and hard photons is difficult to reconcile with an impact. Moreover, the total flux (120–1000 eV, Table 2) of RX J0720 remained almost constant, but the fluxes in the soft and the hard band changed significantly (the spectrum became harder until  $\text{MJD} \approx 53000$  days and now it is softening again, see Figure 3, suggesting the existence of at least two emission regions with different temperatures). The best fit blackbody temperature and size of the emitting area show changes of  $\approx 10 - 20\%$ . However, it is remarkable that these changes somehow conspire to keep the flux within 10% variation, showing that the changes cannot be caused by a sudden heating alone.

In the case of a glitch or an impact, the total flux is expected to increase. The changes indicate a re-arranging of the flux, rather than heating by a glitch. The long-term changes in the absorption feature are also suggestive of some gradual, non-impulsive mechanism behind the timing behaviour of the source. This leads to the conclusion, that the spectral and temporal evolution of RX J0720 might be caused by magnetospheric distortions, hence a re-arranging of the magnetic field. Note, that the broad band luminosity remains constant in the X-rays, but the source was not monitored at optical and UV wavelengths (Motch & Haberl 1998; Motch et al.

2003; Kaplan et al. 2003; Eisenbeiss et al. 2010).

RX J0720 is close to magnetars in the  $P - \dot{P}$  diagram. In particular, evolutionary connections between the M7 and the soft gamma ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) have been discussed by many authors (Heyl & Kulkarni 1998; Kaplan & van Kerkwijk 2009b; Popov et al. 2010). AXPs and SGRs have similar pulse periods and are younger (by a factor of 10 – 100) than the M7. Despite low statistics (only  $\approx 10$  objects in each group are observed) and the unsettled properties of some objects, Popov et al. (2010) have shown that the different families of NSs can be explained by one evolutionary model. A possibility, then, is that the M7 descend from SGRs/AXPs, and are aged magnetars in which the magnetic dipole field decayed from the initial  $\approx 10^{14}$  G to the present  $\approx 10^{13}$  G. The decay of the surface field is actually triggered by the decay of the internal, toroidal and poloidal, one. It is the progressive exhaustion of internal magnetic helicity that is responsible for the low-level activity of old magnetars (bursting/outbursting behaviour, non-thermal X-ray spectral components). The recent discovery of a low-field SGR (Rea et al. 2010) and its likely interpretation as an aged magnetar (Turolla et al. 2011) lends further support to this picture. It could be that, contrary to SGR 0418+5729, the initial internal toroidal field in RX J0720 was not strong enough to power an outburst in its late stages of evolution (Perna & Pons 2011) and the last hiccups of activity are seen as moderate changes in the spectral and timing properties. In this case, we should witness more erratic spectral and temporal irregularities in the future, if the monitoring of RX J0720 will be continued.

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